Active Control of a Robotic Arm with Pneumatic Artificial Muscle Actuator

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ABSTRACT

The paper is on the control of a robotic arm actuated by a pneumatic artificial muscle (PAM) system. A conventional proportional-integral-derivative (PID) controller with active force control (AFC) is employed to control the robot arm assigned to operate a prescribed task. Simulation results show the effectiveness of the proposed control strategy compared to the PID control only scheme. The results of the simulation study demonstrate the intense robustness and effectiveness of the proposed control scheme in countering the loading and operating conditions compared to the PID control scheme.

INTRODUCTION

Pneumatic muscle system was first developed by McKibben in the 1950's as soft actuators in artificial limbs and became commercially available in the 1980's (Caldwell et al., 1993). They have since been used as actuators in high-tech robotic applications, in physical therapy for functional healing and for strength escalation devices involving humans, where the devices have to be self-contained and carried for long distances. McKibben pneumatic artificial muscles (PAM) possess all the advantages of traditional pneumatic actuators (i.e. cheapness, quickness of response, high power/weight and power/volume ratios) without the main drawback (i.e. compliance or sponginess). For this reason, they are finding increased use in robotic systems. PAM technology is currently under study for use in exoskeleton suits to be worn by humans for force and/or mobility assistance. A difficulty inherent in PAM technology for use in precision and/or force applications is the difficulty in controlling them precisely. This is because they are nonlinear and time varying (i.e., since they are made of flexible rubber or plastic, their characteristics vary with temperature and PAM temperature varies with use) (Lilly, 2003). Due to their high nonlinearities, advanced control strategies like adaptive control (Tanaka et al., 1999), adaptive control based on neural networks (Tao and Kokotovic, 1996), nonlinear PID control (Thanh and Ahn, 2006) have been investigated and explored.

In this paper, AFC with PID scheme is proposed in order to improve the control performance of the PAM manipulator. The PID element provides the basic stable and reliable performance while the AFC strategy is used to suppress the disturbance so as to ensure a robust and effectiveness scheme is achieved to control the manipulator actuated by highly nonlinear actuators.

The paper is structured as follows: First, the McKibben pneumatic artificial muscle (PAM) is briefly described in terms of its construction and operation. The next section is on the application of a feedback control method using AFC with PID to a single link mechanical arm. It is followed by modelling and simulation study. The results obtained from the study are discussed in the next section and finally a conclusion is derived with indication for future work and direction of the continuing research study.

PNEUMATIC ARTIFICIAL MUSCLE

The McKibben muscle was invented in the 1950s by physician Joseph L. McKibben with the initial aim of driving an arm orthosis for his poliomyelitic daughter. Even though, at this time, it has been marketed as an orthopedic device (Schulte, 1961), in the 1960s the invention was abandoned in favour of step motors. However, in the 1980s engineers of the Japanese tyre manufacturer Bridgestone proposed a redesigned and more powerful version of the McKibben muscle called the rubbertuator (Inoue, 1988), that was proposed to motorize both soft and powerful robot arms (Eskiizmirliler et al., 2002). Such an artificial muscle – consisting of a braided sheath, according to a double-helix weaving, surrounding a rubber inner tube – is mainly characterized by its initial length L_0, initial radius that is depicted in Fig. 1.

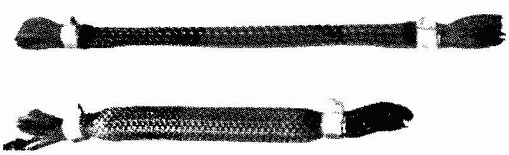

Fig. 1. McKibben pneumatic actuators relaxed (top) and inflated (bottom)-Shadow Company (Aschenbeck et al., 2006)

The general working principle of the PAM is similar to the McKibben actuator, thus the same relationship between pressure, force, and contraction can be used. The following expression of F as a function of the pressure P and the contraction ratio ε is as follows (Tondu et al., 2000):

$$F(P,\varepsilon) = (\pi r_0^2)P[a(1-k\varepsilon)^2 - b] \quad , \quad 0 \le \varepsilon \le \varepsilon_{max} \quad (1)$$

Where

$$\varepsilon = (L_0 - L)/L_0 \quad (2)$$

$$a = 3/\tan^2(\alpha_0) \quad , \quad b = 1/\sin^2(\alpha_0)$$

$$P = P_0 \pm \Delta P \quad (3)$$

An antagonistic pair McKibben muscles is illustrated in Fig. 2. The muscles can drive a single joint robot link in a similar way to how the biceps and triceps rotate the forearm around the elbow. However, unlike natural skeletal muscles, McKibben muscles cannot apply passive tensions since their braided shells are not extensible. Both muscles are inflated at the same pressure P_0 and have the same contraction ratio ε_0 in the initial state in order to keep the robot link in good working order. When the agonist is inflated at pressure P_1, different from the antagonist pressure P_2, an arm rotation of angle is produced as it is depicted in Fig.1. A true energetic transformation is performed because of the basic pantograph network shaped by its helical weaving, which converts inner tube circumferential pressure forces into an axial contraction force F.

The McKibben muscles used in this study have the following parameters: L_0 = 30 cm, r_0 = 0.7 cm, α_0 = 20 and k = 1.30 (Tondu et al., 2000). The initial braid angle α_0 is defined as the angle between the muscle axis and each thread of the braided sheath before expansion.

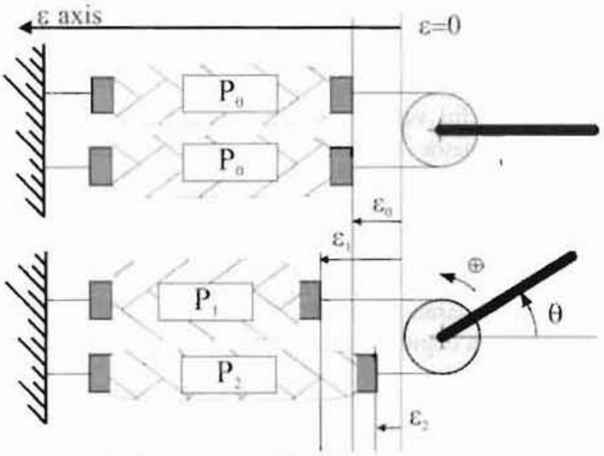

Fig. 2. Antagonistic Mckibben muscle actuator (Eskiizmirliler et al. 2002)

PID CONTROL LOOP

It is represented by the outermost loop of the proposed scheme specially designed to provide for positional trajectory control. The trolley mass displacement and the effect of disturbances, friction can be clearly observed at the controlled variable response (output) of the system. It is used in combination with the AFC scheme since it has been shown that it provides consistently stable though not so robust performance. Also, it is a well-known fact that PID control generally performs excellently for a system with no or little disturbances and operating at a low speed. However, at the commencement of adverse conditions, the performance degrades considerably. The AFC part provides the extra robustness feature through its disturbance rejection capability (Priyandoko et al., 2008). Usually, the PID system is designed prior to the implementation of AFC. The transfer function of a PID controller is given as follows:

$$G_{PID} = K_P + K_I/s + K_D s \quad (4)$$

Where K_P, K_I and K_D are the proportional, integral and derivative gains, respectively. In this study, the Ziegler–Nichols method is employed to tune the PID parameters. Thus the gaind achieved by this method are K_p=1, K_I=8, K_D=0.5.

ACTIVE FORCE CONTROL

Active force control (AFC) strategy was first proposed by Hewit and co-workers to control a dynamic system in order to ensure the system remain stable and robust in the existence of known and unknown disturbances (Hussein et al., 2000). AFC has been demonstrated to be superior compared to conventional methods in controlling a robot arm (Mailah and Rahim, 2000). Fig. 2 illustrates the principle of AFC concept applied to a translational system. AFC can be shown to complement the basic Newton's second law of motion, i.e. for a rotary system:

$$\sum T_q = I\ddot{\theta} \quad (5)$$

Where $\sum T_q$ is the sum of actuated torques, I is the total mass moment of inertia of the body and $\ddot{\theta}$ is the angular acceleration of the rotating mass. In AFC, we can effectively accommodate the disturbances by obtaining the measurements of the acceleration and the torque using physical accelerometer and torque sensor respectively. Referring to Fig. 3, IN is the estimated inertia of the link and $\ddot{\theta}$ is the angular acceleration of the arm. The concept of AFC is to use some measured and estimated values of the identified system parameters namely the actuated torque, acceleration of the body and the estimated inertia of the body.

$$T^{*}_{d} = T_q' - IN\ \ddot{\theta}' \quad (6)$$

Where T^{*}_{d} is the estimated disturbance, IN the estimated inertia, and T_q is the actuated torque. In the study, the actuated torque and acceleration were assumed to perfectly modelled while the estimated inertia is obtained through a crude approximation technique.

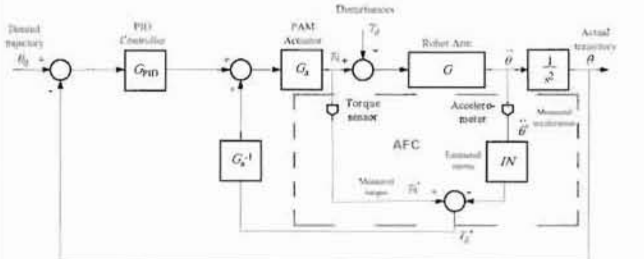

Fig. 3. AFC scheme applied to a single link robot arm actuated by McKibben pneumatic artificial muscle

SIMULATION

The simulation was performed using MATLAB and Simulink software packages. The McKibben model, single link robotic manipulator, PID controller and also AFC are modelled in the Simulink environment. This is depicted in Fig. 4. In addition, the step and sinusoidal inputs were applied to the system to test the system response.

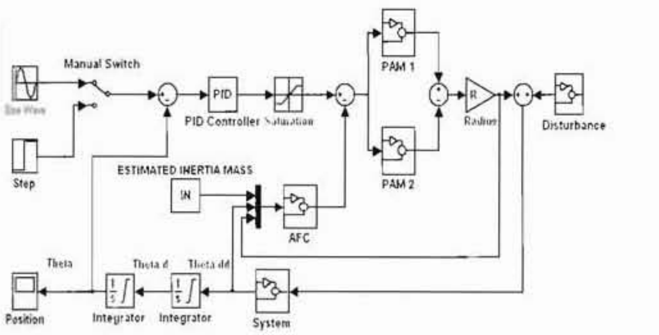

Fig. 4. Simulink diagram of the proposed system

The following parameters were used in the simulation study:

Length of the arm (L): 410 (mm)
Initial pressure (P_0): 3 (bar)
Radius of pulley (R): 15 (mm)
Pretension of PAM: 10 %
Disturbance (step input): 5 N

Additionally, the step input is considered as a disturbance in the simulation study which can be replaced as a friction in the bearing and PAM.

RESULT AND DISCUSSION

AFC was implemented on the single link actuated by PAM. Figs. 7 through 10 shows the results obtained from the simulation study with two different inputs which are step input and sinus respectively.

As can be seen in Figs. 7 to 8 with reference to the desired angle and actual angle, it is very obvious that the AFC method is much more robust and precise than the PID control. The response curve generated by the AFC-based scheme is far less than the PID control. In addition, in Fig. 7 clearly shows the fluctuations which are suppressed by the AFC loop depicted in Fig. 8. The trend in Fig. 8 produced by the AFC-based scheme is steadier than the PID controller. Therefore, the results affirm that the system is more robust and effective. Figs. 9 and 10 exhibit the response of the manipulator under sinusoidal input. In this case, the joint position follows the reference value nearly without lag. To evaluate the influence of the input, the performance using the sinusoidal input shows marginally better result. Thus, it is clear that the AFC based scheme manages to suppress the disturbances effectively during the arm's operation. The results present an important finding that may assist researcher to design and develop a robust tool for a robot arm (or even actual human arm) particularly in the event the end-effector or tooling device attached to the wrist is subjected to various forms of disturbances that include vibration.

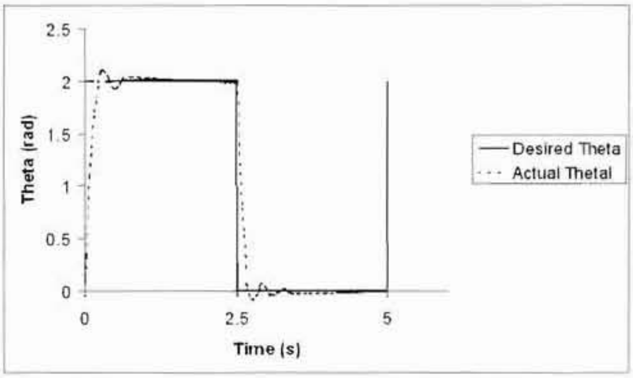

Fig. 5. Response of system controlled by AFC

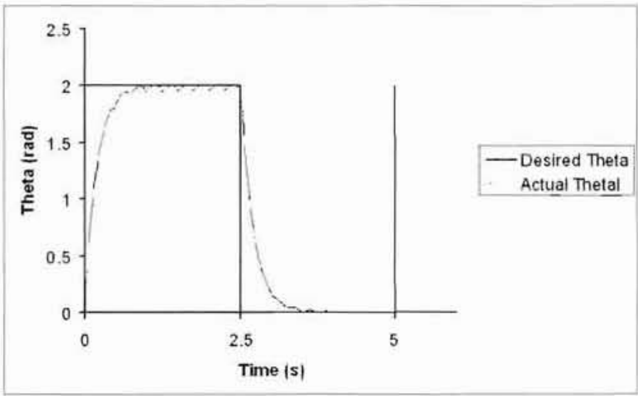

Fig. 6. Response of system controlled by PID

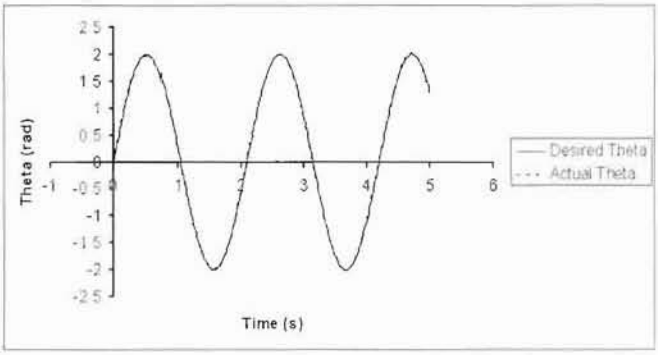

Fig. 7. Response of system controlled by AFC

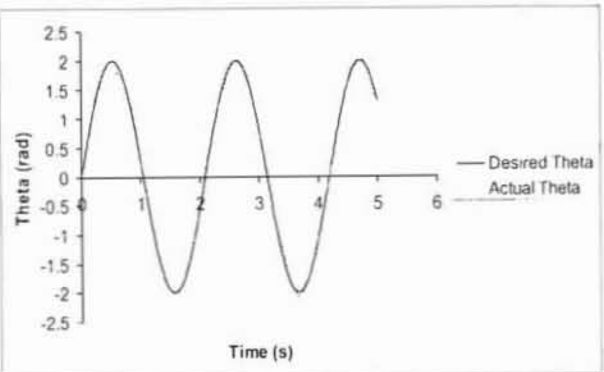

Fig. 8. Response of system controlled by PID

CONCLUSION

The efficiency of the proposed AFC-based control method has been demonstrated on a single link manipulator actuated by PAM. The robustness and accuracy of the proposed system was particularly highlighted in the simulation study. The results may serve as a potential tool in aiding the design and development of a device for use in a Mechatronics robot arm or even human arm. Further research could be carried out to complement the results obtained in the study. This may include investigation of the system subject to the use of artificial intelligence (AI) methods, two links actuated by PAM, and varying loading and operating conditions such as different type of disturbances and speed of operation. Research on the practical implementation of the proposed system is actively on-going and in the final stage of completion.

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